Logically Isolated, Actually Unpredictable?

Measuring Hypervisor Performance in Multi-Tenant SDNs

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ABSTRACT

Ideally, by enabling multi-tenancy, network virtualization allows to improve resource utilization, while providing performance isolation: although the underlying resources are shared, the virtual network appears as a dedicated network to the tenant. However, providing such an illusion is challenging in practice, and over the last years, many expedient approaches have been proposed to provide performance isolation in virtual networks, by enforcing bandwidth reservations.

We in this paper study another source for overheads and unpredictable performance in virtual networks: the hypervisor. The hypervisor is a critical component in multi-tenant environments, but its overhead and influence on performance are hardly understood today. In particular, we focus on OpenFlow-based virtualized Software Defined Networks (vSDNs). Network virtualization is considered a killer application for SDNs: a vSDN allows each tenant to flexibly manage its network from a logically centralized perspective, via a simple API.

For the purpose of our study, we developed a new benchmarking tool for OpenFlow control and data planes, enabling high and consistent OpenFlow message rates. Using our tool, we identify and measure controllable and uncontrollable effects on performance and overhead, including the hypervisor technology, the number of tenants as well as the tenant type, as well as the type of OpenFlow messages.

KEYWORDS

SDN; Virtualization; Hypervisor Performance Benchmark

1 INTRODUCTION

While virtualization has successfully revamped the server business—virtualization is arguably the single most important paradigm behind the success of cloud computing—, other critical components of distributed systems, such as the network, have long been treated as second class citizens. For example, cloud providers hardly offer any guarantees on the network performance today. This is problematic: to provide a predictable application performance, isolation needs to be ensured across *all involved components and resources*. For example, cloud-based applications, including batch processing, streaming, and scale-out databases, generate a significant amount of network traffic and a considerable fraction of their runtime is due to network activity. Indeed, several studies have shown the negative impact network interference can have on the predictability of cloud application performance.

Network virtualization promises a more predictable cloud application performance by providing a unified abstraction and performance isolation across nodes and links, not only within a data center or cloud, but for example also in the wide-area network. Accordingly, over the last years, several virtual network abstractions such as *virtual clusters* [4], as well as systems such as *Oktopus* [4], *Proteus* [26], and *Kraken* [11], have been developed.

While today, the problem of how to exploit resource allocation flexibilities and provide isolation in the data plane is fairly well-understood [4, 8, 11, 26], we in this paper study a less well-understood but critical component in any network virtualization architecture: *the hypervisor*. A hypervisor is responsible for the multiplexing, de-multiplexing, and orchestrating resources across multiple tenants. For example, the hypervisor performs admission control which is needed to avoid over-subscription and provide absolute performance guarantees for tenants sharing a finite infrastructure.

In particular, and as an important case study, we in this paper focus on virtual Software-Defined Networks (vSDNs). Indeed, network virtualization is considered a killer application for Software-Defined Networks (SDNs) [8, 10]: By outsourcing and consolidating the control over data plane devices (OpenFlow switches) to a logically centralized software, the so-called controller, a vSDN allows each tenant to flexibly manage its own virtual network(s), from a logically centralized perspective. In particular, OpenFlow, the de facto SDN standard, offers a simple API for installing packet-forwarding rules, querying traffic statistics, and learning about topology changes.

To give an example of the importance of the hypervisor in vSDNs, we may consider the flow setup process: an SDN controller needs to react to a new flow arrival by installing flow rules on the switch accordingly. In a vSDN, the packet arrival event and flow rule message are communicated indirectly between the controller and the OpenFlow switch, via the hypervisor. Thus, in a scenario where the hypervisor is overloaded, undesired latencies may be introduced. Another example may arise in the context of a load balancing application which requires link utilization statistics every 10 ms: even if a controller can handle high-rate statistics requests, the hypervisor may only supports one OpenFlow request per second, which can degrade the application performance.

As we will see in this paper, the application performance in a multi-tenant SDN is influenced by several additional aspects.

Our Contributions

This paper initiates the study of sources of overheads and unpredictable performance in multi-tenant virtual networks based on SDN. We present a novel benchmarking tool for OpenFlow which we developed for this study, and which is tailored toward high and consistent OpenFlow message rates.

We show that our benchmark tool can help identify sources of overheads and bottlenecks as well as properties of a vSDN architecture, which we hope in turn can help developing models and improve the hypervisor design. In particular, we identify and measure the factors related to the the hypervisor technology and mechanism, the number of tenants as well as the tenant type, and the type of OpenFlow messages.

Organization

The remainder of this paper is organized as follows. Section 2 presents our benchmark tool and measurement methodology. Section 3 reports on our results. After reviewing related work in Section 4, we summarize our contributions and outline future work in Section 5.

2 MEASUREMENT METHODOLOGIES

In order to conduct our study of the performance and overheads of the SDN hypervisor, we first needed to develop a novel and more flexible benchmark tool. This section introduces the *perfbench* tool, and also presents our methodology and experimental setup.

2.1 High Throughput Measurement Tool

Due to the incapability to create high and consistent OpenFlow message rates, *perfbench* is designed to emulate high OpenFlow message rates for providing high throughput-oriented performance benchmarks for SDN networks. *perfbench* can be used for measurements in multi-tenant as well as non-virtualized SDN networks. The tools builds on top of libfluid C++ library [1], which provides the basic implementation and interface of OpenFlow messages. It supports OpenFlow versions 1.0 and 1.3. Figure 1 provides a simplified view of how *perfbench* is designed and also how it is operated in multi-tenant SDN networks.

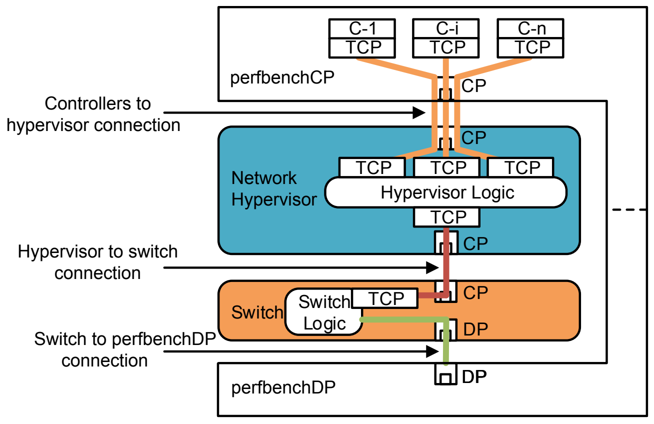


Figure 1: The *perfbench* Architecture

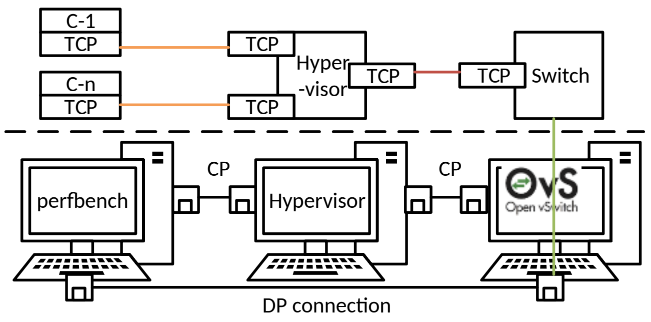


Figure 2: Experimental Setup

2.1.1 *Tool Architecture.*

As illustrated, *perfbench* is divided into two parts, a control plane part (*perfbenchCP*) and a data plane part (*perfbenchDP*). *perfbenchCP* runs the processes for the tenant SDN controllers, i.e., it emulates the tenant SDN controller. Each controller is running in its own thread and is connecting via a unique TCP socket to guarantee isolation between the tenant controllers. For each controller process, a pre-determined constant message rate of OpenFlow messages can be generated: given a certain message rate in seconds, *perfbench* generates an equal distribution of requests at millisecond precision.

perfbenchDP runs the data plane part of *perfbench*. While it can be connected to existing OpenFlow switches directly, e.g., to receive UDP packets sent via `OFPT_PACKET_OUT` messages, it can also emulate OpenFlow switches. In case it emulates an OpenFlow switch, it connects directly to the hypervisor's control plane mode. This operation mode can be useful to just benchmark the real overhead as induced by hypervisors. In this paper, we are operating *perfbench* only in the first mode, i.e., we are not emulating OpenFlow SDN switches.

Table 1: Measurement setups and Configurations

OF Message Type	Tenants	Switch-only	Message Rate	TCP_NODELAY	Hypervisors	No. of runs	Duration
OFPT_PACKET_IN	1	No	10k,20k,30k,40k	0	FV,OVX	10	30 sec
OFPC_PORT_STATS	1	No	5k,6k,7k,8k	0	FV,OVX	10	30 sec
OFPT_PACKET_IN	2 : 20	Yes	40K	0/1	FV,OVX	10	30 sec
OFPT_PACKET_OUT	2 : 20	No	60K	0/1	FV,OVX	10	30 sec

2.1.2 Supported Message Types & Latency. *perfbench* supports the following message types: OFPT_PACKET_IN, OFPT_PACKET_OUT, OFPT_ECHO_REQUEST, OFPT_FEATURES_REQUEST, OFPC_PORT_STATS. For synchronous OpenFlow messages, i.e., where a request expects an answer, e.g., OFPC_PORT_STATS, OFPT_ECHO_REQUEST, OFPT_FEATURES_REQUEST, the latency is measured as the time it takes from sending the request until receiving the reply.

In case of asynchronous OpenFlow messages, namely OFPT_PACKET_IN and PACKET_OUT, the latency calculation is slightly different. For PACKET_IN, *perfbenchDP* sends UDP packets for each tenant via its data plane connection. The latency is then calculated as the time it takes from sending the UDP packet until receiving the OFPT_PACKET_IN at *perfbenchCP*.

For PACKET_OUT, *perfbenchCP* triggers the sending of OFPT_PACKET_OUT with artificial data packets. The latency is then calculated for each tenant as the time it takes from sending the OFPT_PACKET_OUT until receiving the artificial data packet at *perfbenchDP*.

Besides, *perfbench* provides the capability to set the TCP_NODELAY flag for a specific TCP connection. Setting TCP_NODELAY disables Nagle's algorithm. While Nagle's algorithm has been introduced to improve network performance in general, as we will see, it can lead to performance costs in case of SDN-based networks. Nagle is used to aggregate more data, thus produce less packet overhead per TCP packet. However, this aggregation of packet content might lead to higher latencies per packet. As SDN application performance can be severely affected by high delays, Nagle's algorithm hence might lead to performance degradation in SDN networks. Accordingly, to investigate the impact of Nagle, *perfbench* provides the capability to set TCP_NODELAY .

2.2 Measurement Setup and Test Cases

Figure 2 shows the measurement setup. Three PCs are used to conduct the hypervisor performance benchmarks in this paper. *perfbench* (*perfbenchCP* and *perfbenchDP*) runs on the left PC, one hypervisor (FV or OVX) on the middle PC, and an OpenVSwitch (OVS) [18] instance on the right PC. perfbenchCP is connected to the hypervisor PC. The hypervisor PC is connected to the OVS PC. perfbenchDP is connected via a dedicated line to the data plane part of the OVS PC.

For a short representative measurement study, we choose OFPT_PACKET_IN and OFPT_PACKET_OUT for asynchronous message types, and OFPC_PORT_STATS for synchronous message types. OFPT_FEATURES_REQUEST and OFPT_ECHO_REQUEST are neglected as we see them as not critical for the runtime performance of SDN networks.

Table 1 provides an overview of all conducted measurements. For all message types, single tenant (1) as well as multi-tenant (2:20) measurements are conducted for a range of rates, TCP_NODELAY settings, and the two hypervisors FlowVisor (FV) and OpenVirteX (OVX). Every setup is repeated 30 times for a duration of 30 seconds. As we are interested in the steady-state performance, we cut the first and last 5 seconds from the data analysis; the remaining 20 seconds show a stable pattern.

For the multi-tenancy measurements, the hypervisor instances are configured according to their specificity. This means, for instance, that for OVX *perfbenchDP* uses artificial unique MAC addresses per tenant as this is a pre-requisite for the operation of OVX. As FV uses flowspace slicing, such a setting is not necessary.

3 MEASUREMENTS AND EVALUATION

We structure our measurement study into two parts: single tenant experiments and multi tenant experiments. In the first part, we investigate how different hypervisor implementations affect the control plane performance, as well as how the performance depends on the OpenFlow message types. In the second part, we investigate whether and how the control latency depends on the number of tenants, and how the tenants' controller impact the hypervisor performance. Finally, we take a brief look at fairness aspects.

3.1 Single Tenant Evaluation

The hypervisor performance is evaluated in terms of control plane latency, and compared against different control message rates. We compare two state-of-the-art hypervisor implementations, namely FlowVisor (FV) and OpenVirteX (OVX). Moreover, we consider the performance for two OpenFlow message types, namely asynchronous and synchronous messages (see above). We consider asynchronous OFPT_PACKET_IN messages in our experiments since their performance is critical for flow setup. For synchronous messages, we consider OFPC_PORT_STATS as an example: it is used by SDN apps to collect port statistics, e.g., for load balancing or congestion-aware routing.

Fig. 3a shows the control plane performance overhead induced by the indirection via the hypervisor: a “man-in-the-middle” between controllers and switches. The evaluation considers a setting where OFPT_PACKET_IN messages are arriving at a rate of 40k per second, which is the maximum rate for this OpenFlow message type that can be generated by our tool on the used computing platform. The control plane performance is considered in terms of the control plane latency, where FV shows an average of 1 ms (millisecond) compared to 0.1 ms with the switch-only. OVX adds even more latency overhead with 3 ms compared to an 0.3 with switch-only. The control latency overhead could be observed for both FV and OVX, due to adding extra intermediate network processing.

How do different hypervisor implementations affect the control plane performance?

In order to evaluate the difference between the hypervisor implementations, we evaluate the observations from the measurements of the OFPT_PACKET_IN OpenFlow messages, shown in Fig 3b. The OFPT_PACKET_IN message rate is ranging from 10k to 40k messages per second.

The measurements show that FV features a lower control latency than OVX, especially with increasing message rates. OVX shows higher latency and more outliers with varying rates due to the control message translation process, e.g., an average of 1 ms for 10K up to an average of 3 ms for 40k. This is because OVX includes data plane packet header re-writing from a given virtual IP address specified for each tenant to a physical IP address used in the network. Also note the outliers with OVX at 40k, indicating a possible source of unpredictable performance. In contrast, FV operates in a transparent manner where it does not change the data plane packet headers and it operates with an average of 1 ms control latency for all evaluated rates. The OFPT_PACKET_IN handling at FlowVisor results in lower control latency and a more robust performance under varying control rates.

How does the performance change with different OpenFlow message types?

For this evaluation, we also consider a single tenant, however measuring the control latency for OFPC_PORT_STATS messages. The measurement is carried out at message rates between 5k and 8k per second, due to the limits of the OFPC_PORT_STATS rate the used switch can handle. As shown in Fig. 3c, the transparent design shows ineffiency and overhead in terms of control latency for OFPC_PORT_STATS , e.g., going from an average of 1 ms with 5k up to an average of 7 ms at 8k. Since FV transparentely forwards all message to the switch, the switch can become overloaded, hence, the control latency increases proportionally to the port stats rates. The switch becomes overloaded at a rate of 8k OFPC_PORT_STATS per second. OVX uses a different implementation for synchronous messages: it does not forward the port stats to the switches, but rather pulls it from the switch given the number per second. OVX replies on behalf of the switch to all other requests, and hence, avoids overloading the switch, resulting in a better control plane latency performance. However, we also note a drop between 5k and 6k for OVX, indicating a source of unpredictability.

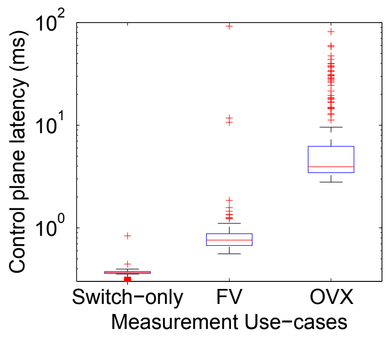
3.2 Multi Tennant Evaluation

We study how the vSDN performance depends on the number of deployed tenants. Recall that ideally, in a virtual network, the performance should not depend on the presence or number of other tenants. We also measure the influence of the tenant’s controller implementation on the hypervisor performance. For this purpose, we consider two implementations for the tenant’s controller considering the packaging of OpenFlow messages to TCP packets. The controller can either aggregate multiple OpenFlow messages in a TCP packet, which we refer in short as (AGG). Alternatively, the controller can exploit the TCP_NODELAY setting and send each OpenFlow message once it is generated in a TCP packet, which we refer to by (ND).

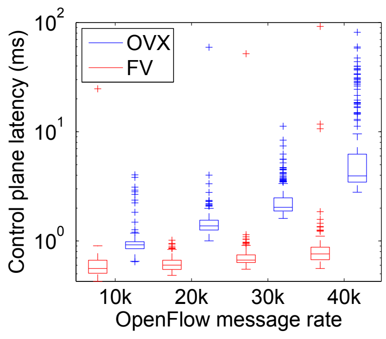
How does the performance, i.e., control latency, change with increasing number of tennants?

For the multi tenant evaluation, we use OFPT_PACKET_OUT OpenFlow messages, since they originate from the tenant’s controller and can be influenced by the controller implementation. We iterate from 2 tenants up to 20 tenants deployed on the hypervisor: for comparison purposes, we adjust the per-tenant message rate such that the total rate remains constant. The OFPT_PACKET_OUT message rate used in this evaluation is 60k messages per second.

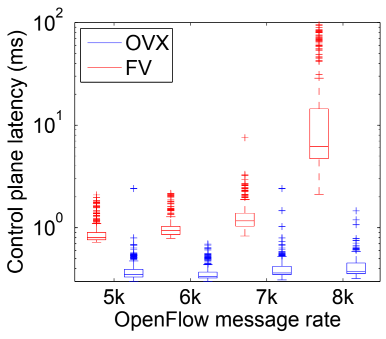
The impact of increasing the number of tenants is shown in Fig. 4. We discuss first the impact of increasing the tenants on both FV and OVX with the default controller implementation with TCP_NODELAY = 0, i.e., aggregation of several OpenFlow messages on the same TCP packet. For both hypervisors, depicted as “FV-AGG” and “OVX-AGG”, increasing the number of tenants degrades the performance of the control plane and adds more latency overhead. However, this is mainly driven by the setting of the tenant’s controller, where the controller adds waiting time till enough OpenFlow messages are there to be sent on a TCP packet. For example with a fixed 60k OFPT_PACKET_OUT, at 2 tenants, each tenant generates 30k messages per second, however at 20 tenants, each tenant only generates 6k messages per second. Hence, controller of each tenant at 20 tenants experiences waiting times till enough OpenFlow messages are available to be sent on a TCP packet, i.e., aggregation. This behavior results in control latency of an average 6 ms compared to 3 ms only at



(a) Hypervisors overhead, Single tenant, OFPT_PACKET_IN , 40k rate



(b) FV vs. OVX, Single tenant, OFPT_PACKET_IN , 10-40k rate



(c) FV vs. OVX, Single tenant, OFPC_PORT_STATS , 5-8k rate

Figure 3: Single tenant, latency

2 tenants, with OVX-AGG for example. Another remark is that OVX shows more control plane latency than FV for OFPT_PACKET_OUT messages, similar to the control latency observations for OFPT_PACKET_IN messages.

How does the tenant's controller impact the hypervisor performance?

The impact of the tenant's controller implementation is shown in in Fig. 4, depicted for both hypervisors as "FV-ND" and ''OVX-ND". Using the TCP_NODELAY =1 at the tenant's controller, both hypervisors show a significant improvement compared to the OpenFlow aggregation implementation such that the control latency becomes decoupled from the number of deployed tenants. FV results in a control latency of, on average, less than 1 ms, independentl of the number of tenants, while OVX results in 3 ms for all tenants. The TCP_NODELAY setting allows the generated OpenFlow messages to be sent directly, while message aggregation on TCP connection adds to the control latency: OpenFlow messages have to wait at the controller after being generated. Note that the hypervisor cannot control the tenant's controller behavior, which introduces a source of unpredictability.

The workload of the hypervisors, in terms of CPU utilization, for both FV and OVX is shown in Fig. 5. Note that OVX is multi-threaded, hence can utilize more than 1 CPU core, compared to FV which is only single threaded. The first insight is that FV requires much less CPU to process the same OpenFlow packet type and rate, e.g., 50% of 1 CPU core with aggregation, in this setting at a OFPT_PACKET_OUT rate of 60k per second. Considering the difference in the CPU utilization, comparing the TCP_NODELAY setting, the CPU utilization is higher compared to aggregation, for both FV and OVX. For example, OVX utilizes 50% more CPU at 20 tenants with TCP_NODELAY = 1. It is intuitive to see that in case TCP_NODELAY flag is enabled, more TCP packets are generated by the tenant and have to be processed by the hypervisor which increases the hypervisor's CPU load.

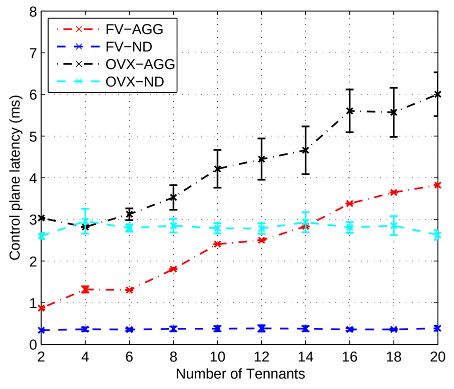


Figure 4: Multiple tenants, OFPT_PACKET_OUT , 60k rate, latency

How is the observed control latency distributed among the multi tennants, i.e., fairness?

In order to investigate the perforamnce impact on individual tenants, we measure the latency per tenant for the setup with OFPT_PACKET_OUT , with 60k rate and for 20 tenants, i.e., max setup/settings. The control plane latency distribution over a single run is shown in fig 6 for both hypervisors and TCP_NODELAY = 0 and = 1.

In general, we could observe fair latency distribution among all 20 tenants, except for the the case with OVX and aggregation, in Fig. 6c. There are 3 out of 20 tenants which experience a control latency with an average of 0.5 ms, while all other tenants experience an average control latency of 6 ms. This defines the control latency guarantees that can be provided by the hypervisor, which requires considering the

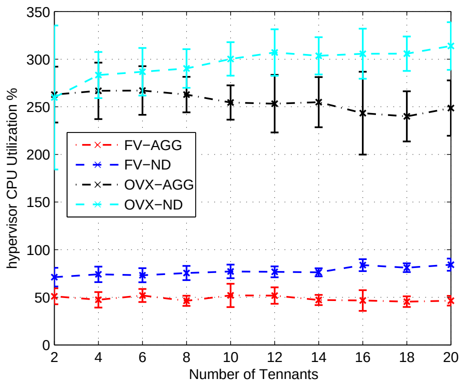


Figure 5: Multiple tenants, `OFPT_PACKET_OUT` , 60k rate, CPU

worst not the best latency performance. This can result in unpredictabiliy and unfairness.

4 RELATED WORK

There exists a large body of literature on overheads and sources of unpredictable performance in cloud applications. For example, several studies have reported on the significant variance of the bandwidth available to tenants in the absence of network virtualization: the bandwidth may very by a factor of five or more [28], even within the same day. Given the time spent in network activity by these applications, this variability has a non-negligible impact on the application performance, which makes it impossible for tenants to accurately estimate the execution time in advance. Accordingly, over the last years, many network virtualization architectures and prototypes have been proposed, leveraging admission control and bandwidth reservations and enabling tenants to specify absolute guarantees [4, 12, 16, 19, 20, 25, 26].

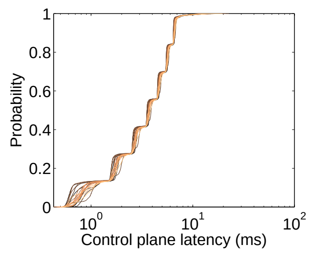
There already exists a large body of literature on hypervisors as well. We in this paper are particularly interested in hypervisors for SDN, and we refer the reader to Blenk et al. [5] for a good survey. Existing SDN hypervisors can be classified into two categories: centralized (e.g., [22]) and distributed (e.g., [8]). FlowVisor [22] is one of the most well-known hypervisors today. FlowVisor assigns different tenants to different sub-spaces of the header field space (so-called flow spaces), and provides isolation (both in terms of address space as well as in terms of resources) in the data plane. FlowVisor has already been extended in several directions, e.g., with an intermediate control plane slicing layer that contains a *Flowspace Slicing Policy (FSP)* [3] engine, or with improved abstraction mechanisms [7, 21]. *Enhanced FlowVisor* [17], based on NOX, adds bandwidth reservations (using VLAN PCP) and admission control. *Slices Isolator* [9] is positioned between the physical SDN network and the virtual SDN controllers, and allows to adapt the isolation demands of the virtual network users. *FlowN* [8] is the first distributed hypervisor for virtualizing SDN networks. It is based on container virtualization and does not provide tenants with their own virtual SDN controller. Instead of only slicing the physical network, FlowN completely abstracts the physical network and provides virtual network topologies to the tenants. *OpenVirteX* [2] provides address and topology virtualization, by operating as an intermediate layer between the virtual SDNs and controllers.

Interestingly, although a hypervisor lies at the heart of any multi-tenant and network virtualized system, the hypervisor and especially its performance and possible overheads have received little attention: a gap which we aim to fill with our paper. Indeed, the survey by Blenk et al. [5] states a comprehensive performance evaluation framework as a main open problem for future research.

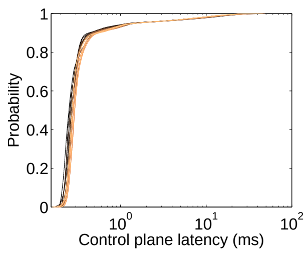
Finally, there also exists a comprehensive list of literature on OpenFlow performance and measurements. For example, Hendriks et al. [13] consider the suitability of OpenFlow as a traffic measurement tool (see [27] for a survey on the topic), and show that the quality of actual measured data can be questionable: The authors demonstrate that inconsistencies and measurement artifacts can be found due to particularities of different OpenFlow implementations, making it impractical to deploy an OpenFlow measurement-based approach in a network consisting of devices from multiple vendors. In addition, they show that the accuracy of measured packet and byte counts and duration for flows vary among the tested devices, and in some cases counters are not even implemented for the sake of forwarding performance. Also other authors observed inconsistencies between bandwidth measurements results and and a packet-based ground truths [24]. OpenFlow monitoring systems are implemented similarly to NetFlow, and accordingly, problems regarding insufficient timestamp resolution [14, 23], and device artifacts [6] also apply. Finally, Kuźniar et al. [15] report on the performance characteristics of flow table updates in different hardware OpenFlow switches, and highlight differences between the OpenFlow specification and its implementations, which may threaten correctness or even network security.

5 CONCLUSIONS

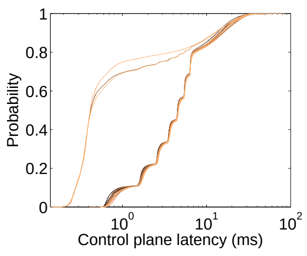
We in this paper initiated the empirical study of performance costs related to the hypervisor in an SDN-based virtual network. We argued that the hypervisor is a critical but not well-understood component in any network virtualization environment supporting multi-tenancy in general, and in SDNs in particular: as requests from the controller and replies as well as notifications from the OpenFlow devices have to pass through the hypervisor, the tenant's application performance



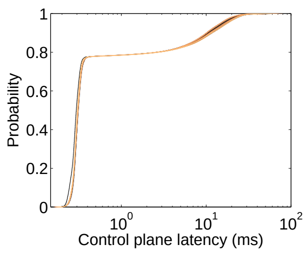
(a) FV, TCP_NODELAY = 0



(b) FV, TCP_NODELAY = 1



(c) OVX, TCP_NODELAY = 0



(d) OVX, TCP_NODELAY = 1

Figure 6: 20 Tenants, OFPT_PACKET_OUT , 60k rate, Latency distribution for each tenant

is highly influenced by the performance of the hypervisor and its workload.

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